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Health Impacts from Diesel Freight Emissions: Development of a Geospatial Analytical Framework for Policy Evaluation with a Case Study of Sacramento, CA

**Masters in Science, Technology, and Public Policy Thesis Submitted in
Fulfillment of the Graduation Requirements for the**

**College of Liberal Arts/Public Policy Program at
ROCHESTER INSTITUTE OF TECHNOLOGY**

Rochester, New York

May, 2008

Submitted by:

Colin Murphy

Student Name

(Signature)

(Date)

Accepted by:

James J. Winebrake – STS/Public Policy

Faculty Advisor

(Signature)

(Date)

Karl Korfmacher – Environmental Sciences

Thesis Committee Member

(Signature)

(Date)

J. Scott Hawker – Software Engineering

Thesis Committee Member

(Signature)

(Date)

Franz Foltz

Graduate Coordinator

(Signature)

(Date)

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Abstract

Diesel particulate matter, emitted by many types of freight transport, poses a health risk to populations living near freight activity. Accurate information about the magnitude and location of health impacts would help inform policy decisions at a number of levels. Existing methods, including atmospheric dispersion modeling, epidemiology or air quality measurement can estimate the magnitude of harm experienced by populations but these methods often require resources or expertise beyond the reach of some stakeholders, particularly those at local levels. This thesis describes a framework by which health impact estimation can be carried out utilizing readily available models and methodologies in a more simple fashion. This framework postulates that significant parts of the analytic process can be automated by computer scripts or other programmatic structures, thereby reducing the time, expertise and resource requirements for health impact analyses. These analyses will allow policy makers to more effectively evaluate the expected health impacts of transport policy and incorporate public health considerations into other policy making activities. This thesis assembles the analytic tools required for these analyses and outlines the ways in which they might be joined into a single piece of software; though the actual creation of this software is left to future work. A case study of on-highway truck activity in Sacramento, CA utilizes this analytic framework. This case study demonstrates framework and also highlights some possible policy directions for transport in the region.

Introduction

Prior research has clearly demonstrated the threat combustion products of fossil fuels pose to human health (Alberini & Krupnick, 1997; Corbett et al., 2007; Glorennec & Monroux, 2007; Kunzli et al., 2000; Lippmann, Ito, Nadas, & Burnett, 2000; Maitre, Bonnetterre, Huillard, Sabitier, & Gaudemaris, 2006; Pope et al., 2004; Samet, Zeger et al., 2000; U.S. Environmental Protection Agency, 2002). Exposure to exhaust gasses is a significant risk factor for respiratory and cardiovascular disease and there is mounting evidence that sustained, low-level exposure to airborne pollutants causes endocrinal and metabolic damage as well. In particular, emissions from diesel engines, which dominate freight transport, have been linked to negative health consequences (Pope et al., 2002; Pope et al., 2004), largely due to their comparatively high level of particulate matter (PM) emissions.

Despite the known health risks, emission-intensive freight activities continue to increase in the U.S., as well as abroad (EIA, 2006). In many cases, freight transport routes pass near residential areas (Bae, Sandlin, Bassok, & Kim, 2007). Several factors promote the expansion of harmful activities. Marginal health costs can be quite small for any given emissions source, though the sum of multiple sources over time is often significant. Additionally, precise prediction of health impacts for any source or group of sources can often be difficult.

While establishing a causal link between economic activity and health consequences is complicated, it is easy to establish a causal link between economic activity and economic benefits; e.g. it is hard to quantify how many people will become sick as a result of a new rail yard, but easy to quantify the number of jobs, tax revenue etc. that the yard would provide. Freight transport supports many

kinds of commercial and industrial activity and creates approximately 9 million jobs in the U.S. (Bureau of Labor Statistics, 2008). When faced with the choice between access to a clearly defined, strongly desired consumer good and avoidance of a vague, uncertain harm to the environment, many rational actors take the clear, immediate benefit.

The contrast between the uncertain causal links of freight health impacts and the clear causality of freight economic benefits represents an information asymmetry. This is a major reason why existing markets have found it hard to moderate the harms of pollution. In fact, market activity is typically the driving force behind increasing pollution levels. One policy intervention to address the harms from diesel freight pollution is to resolve this information asymmetry. This is particularly relevant in the case of freight transport, which is often a less-studied byproduct of economic development.

Through computer simulation and analysis, existing research has demonstrated how to establish a causal link between emissions and health impacts, but such prediction typically occurs on a location-by-location basis and involves significant cost. This creates an access barrier for policy actors with limited resources or expertise, since conducting analyses on all projects within their jurisdiction may be cost prohibitive or require the use of a modeling expert, using currently available methods.

The problem I will address with this thesis is how to reduce these barriers responsible for the information asymmetry in environmental decision making. The solution will focus on one method for increasing the amount of information regarding health impacts from diesel emissions: a generalizable computational analytic framework for modeling the health impacts of diesel emissions from freight transport. The purpose of this thesis is to assemble an analytic “toolkit” needed to conduct these analyses, describe how such a model would be created, and demonstrate its use. While the ultimate

goal, to improve policy makers' ability to conduct spatially located health impact analyses, may require computational techniques beyond the scope of the immediate project (as well as beyond the author's ability), the fundamental components of such a model will be demonstrated here.

The analytic framework described by this thesis must include all steps in the pollution "cycle": emission of pollutants from diesel combustion, dispersion of those pollutants through the atmosphere, population exposure and health impacts. The intent is that the tool produced by this thesis will be appropriate for limited investigation of freight emissions for local and regional policy planning. This will differ from existing health risk assessment tools in two main ways: it will focus on quantification of expected impacts, rather than attainment of threshold levels of pollutants, and it will be somewhat less comprehensive than conventional risk assessments. Additionally, it should serve as a framework for the development of a more comprehensive system of pollution health impact modeling. This will allow policy makers the opportunity to better predict health impacts of economic development when planning freight transportation and distribution systems.

Literature Review

The threat to human health from diesel emissions is well documented (Alberini & Krupnick, 1997; Corbett et al., 2007; Glorennec & Monroux, 2007; Kunzli et al., 2000; Lippmann et al., 2000; Maitre et al., 2006; Pope et al., 2004; Samet, Zeger et al., 2000). The origin of emissions (fossil fuel combustion) and terminal health impacts (cancer, cardiovascular disease, etc.) are already well understood. But pollution emissions come from a variety of sources, and monitoring activities often report composite levels, making it difficult to link health and environmental impacts to varied sources from a specific location. For example, many ports complete emission inventories which characterize the total emissions from their facility, but it can be difficult to determine what fraction of the total is produced by idling trucks or cargo handling equipment. Predictive modeling of the sort intended by this thesis requires a systematic examination of pollutant activity between origin and termination.

Several computational models have been generated that characterize part of the activity of pollutants. These will be discussed in greater detail later in this section. What appears to be missing is a single toolkit for evaluating the complete pollution-health impact cycle, from emission to exposure and harm quantification. The purpose of this thesis is to mark the path that such a unified toolkit would need to follow.

For clarity, I will break down the activity of toxic air pollution into three stages. The first is the emission of pollutants by vehicles. The second stage is the dispersion of pollutants from their point of emission to the point at which they come into contact with people. The third stage is the uptake of pollutants by humans and the subsequent physiologic damage they suffer. Individually, all three stages

have been well studied and reported in literature. Existing literature is rich with discussions about the most appropriate methods of measurement and importance of confounding factors, so part of this project will be to assess and select measurement and analytic techniques.

The greater question is how all three phases of analysis might be integrated into a single tool, which would simplify the process of health impact analysis. This thesis will attempt to answer this question and describe a framework along which a single tool could streamline the process of analysis.

Pollutant Emission

The link between internal combustion engines and pollutants has been thoroughly researched and conclusively proven for almost half a century. The link between car exhaust and the smog problem of Los Angeles has been documented as early as 1954 (Air Pollution Foundation). A multitude of studies since then have refined the knowledge of diesel emissions (FHWA, 2005). Several recent groups have summarized the total effects of emissions on the environment, notably the Environmental Defense Fund in their report *Global Warming on the Road* (2006), the World Business Council for Sustainable Development in *Facts and Trends to 2050* (2004), and the Oak Ridge National Laboratories in their annual *Transportation Energy Data Book* (2007).

The first question that should be asked is what pollutants are to be considered, for the purposes of this project? Combustion of diesel fuel is known to release many health-hazardous compounds including CO₂, CO, NO_x, SO_x, Volatile Organic Compounds (VOC's), Ozone, and Particulate Matter (PM). Each presents a unique set of health problems (Bae et al., 2007; Nel, 2005; Samet, Dominici, Zeger, Schwartz, & Dockery, 2000; Schwartz, 2000; Stieb, Doiron, Blagden, & Burnett, 2005). Of particular

interest to the question of freight transport are SO_x , VOCs and PM, which are produced in significantly higher proportion by the diesel engines used for freight transport than by gasoline-burning passenger vehicles.

This model focuses on the health impacts of PM and does not specifically model the effects of CO_2 , CO, NO_x , SO_x , VOC's and Ozone. PM is typically broken down by the size of particles; PM_{10} refers to particles less than 10 microns in diameter, while $\text{PM}_{2.5}$ are those less than 2.5 microns in diameter. Typically, the majority of PM_{10} is, in fact, 2.5 microns in diameter or smaller. Estimates of the fraction of PM_{10} smaller than 2.5 microns range from 55-80%, depending on sample location and measurement techniques (U.S. Environmental Protection Agency, 2004). PM is typically a localized pollutant, while the others often produce impacts at the super-regional and global levels. The framework described in this thesis is focused on local impacts and dispersion, so modeling the other pollutants, while possible, will require additional research and data collection at the local level.

A detailed account of emissions from modern internal combustion engines is found in the Greenhouse Gasses, Regulated Emissions and Energy Use in Transportation (GREET) model. This toolkit, developed by the Argonne National Laboratory, examines the total fuel cycle for alternative fuels in order to create a mathematical model for average emissions per mile of vehicles on the road (Wang M.Q., 2001). While the GREET model focuses on alternative fuel vehicles, an analysis of existing heavy-duty diesel trucks was included to allow quantification of emissions from fuel transport. Accurate emissions factors for the current diesel truck fleet are difficult to find, so the figure provided in GREET is the best available representative figure. Most emission models, including the one used in this thesis, treat emission factors as an exogenous input and can be modified to reflect updated or alternative data (see: Methodology).

Other authors have offered alternative emission factors. Abu-Allaban et. al. (2003) uses a multi-lag regression model to estimate on-road emissions from both heavy and light-duty diesel engines and also presents the results of many other authors. Abu-Allaban finds PM_{10} emissions factors for high-speed roads many times greater than those of GREET. However his sampling methods are strongly affected by resuspended road dust and his measurements were taken largely in Reno, Nevada, which, due to its high-desert climate, may have very different dust conditions than other cities. Other authors have conducted dynamometer tests on older diesel vehicles that have been in use for several years, to determine tailpipe emissions under real-life conditions (Ubanwa, Burnette, Kishan, & Fritz, 2003). The test pattern used by that research team is based off those of an EPA standard emission test. The results are intended to model emissions during urban stop-and-go driving, and the resulting emission factors reported in Ubanwa, Burnette, Kishan, and Fritz (2003) are significantly higher (though in the same order of magnitude) than those of GREET.

In addition to existing literature, there is a model under development at the Rochester Institute of Technology (RIT) that could further inform the discussion of PM emissions from freight transport, the Geographic Intermodal Freight Transport (GIFT) model (Winebrake et al., 2008). GIFT is a Geographic Information Systems (GIS) based model of inter-modal freight transport. It produces emissions data (amounts, distribution and time dependencies), but also accounts for inter-modal transfer, which generates a significant amount of diesel emissions (Winebrake et al., 2007). This would be ideal for generating health impact analysis, since it could, possibly, allow for the comparison of relative impacts of different transport methods. Additionally, the GIFT model analyzes emissions at intermodal transfer facilities. The analytic framework under development is primarily concerned with estimation of health

impacts from truck activity, but it may also be important to evaluate the impacts of freight handling and processing at transfer points.

Ultimately, a pre-existing GIS model may not be required for the purposes of this thesis. Since this project is primarily concerned with the dispersion and health impacts of freight pollution, pollutant sources could easily be user-defined. For example, if the model was being used to evaluate the impact of increased freight traffic on a given road, the user could specify the additional number of trucks per day and determine the amount and distribution of emissions by using the location of the road, the number of trucks and the amount of emissions per truck-mile from a package such as GREET. With those definitions in place, determining the amount and distribution of pollutants could be accomplished using well-documented methodology. Pollutant amounts will be the product of truck-miles times the truck emissions per mile. Distribution will be achieved through methods discussed in the next section.

Pollutant Dispersion

This stage of the model involves the transport of pollutants from the point of emission to the point of contact with humans. This area has been well researched in terms of point-source pollutant dispersion. Rolling sources have not been specifically addressed in as much detail, though established literature accepts that the time-scaled approximation of rolling sources as line sources is appropriate under normal conditions (Brzozowski, 2006).

Once the initial emissions map is generated, the problem of dispersion comes into play. There are many ways to approach dispersion but they fall into two main categories: atmospheric modeling and Gaussian dispersion.

Several atmospheric models for the spread of pollution have been developed. Each includes elements of terrain modeling, wind dynamics and atmospheric chemistry. If given sound input parameters, they produce accurate maps of concentration levels. The downside is that they can be complicated to use, both in terms of the level of knowledge and skill needed to appropriately operate them and in terms of the initial condition data that must be supplied. This often places them out of reach for many policy makers or analysts.

The U.S. Environmental Protection Agency has commissioned several pollution dispersion models, including CALPUFF and AEROMOD. Both appear to be well suited for the purpose at hand. CALPUFF allows for simulations of multiple species of pollutant, over long distances and through both continuous (“plume”) or interrupted (“puff”) emissions (U.S. Environmental Protection Agency, 2006). AEROMOD is more regionally focused, works primarily with a single species of pollutant and takes complicated terrain into account (U.S. Environmental Protection Agency, 2007a). In addition, dispersion packages such as REMSAD or CMAQ are available. REMSAD is intended to focus on continental-scale dispersion while CMAQ allows for a wide variety of scale options, but is very computationally intensive.

The subject of pollution dispersion has also been addressed outside of the U.S. Australia’s research and development agency, the Commonwealth Scientific and Industrial Research Organization (CSIRO) has developed an atmospheric pollutant modeling package called The Air Pollution Model (TAPM) that utilizes detailed meteorological data to generate an expected dispersion pattern for any given area (CSIRO, 2007). Utilizing this dispersion pattern, atmospheric pollution dispersion can be modeled for any country that maintains adequate atmospheric records.

Another alternative, the Atmospheric Dispersion Modeling System (ADMS) incorporates advanced Gaussian dispersion, complex terrain modeling, atmospheric chemistry and deposition models capable of producing spatially resolved emissions maps of dispersed pollutants (Carruthers et al., 1994; CERC, 2008). ADMS is used by several European environmental ministries to evaluate air pollution issues and has been validated using well accepted methodology (Carruthers, S Dyster, & D.J.McHugh, 2000; CERC, undated). While I cannot speak to the relative accuracy of ADMS as compared to EPA models, it has one significant advantage for the purposes of this thesis: simplicity of interface. I have modest experience in atmospheric dispersion, and ADMS is more accessible to non-experts than the EPA models. While I doubt that I will be able to fully take advantage of the advanced modeling characteristics of ADMS, it does allow for greater accuracy than a simple Gaussian dispersion due to its inclusion of boundary layer thickness, wind speed, surface roughness and PM deposition behavior. ADMS also provides accepted default values for these characteristics, to allow for analyses in situations where comprehensive meteorological data are unavailable.

Though atmospheric modeling can be a tremendously powerful tool for predicting pollutant dispersion, it is a complicated and knowledge-intensive method of action. A more simple method assumes minimal wind, terrain and atmospheric chemistry effects and utilizes a mathematical prediction of Gaussian pollutant dispersion. This model assumes that pollutant concentrations will have normal cross-sectional concentration gradients and that diffusion along these gradients is the dominant mode of pollutant movement. Simple Gaussian models are basic approximations of pollutant dispersion under uncomplicated conditions. More complicated analyses can also be accomplished using the basic Gaussian model.

A study of ultra-fine particles in the vicinity of a Los Angeles highway described their pattern of dispersion, operationalizing the pattern in a way that could be used in a model such as what I am considering (Zhu, Hinds, Kim, Shen, & Sioutas, 2002). Zhu found that under low-wind conditions, particle concentration experienced exponential decay as distance increased from the emission source. Several other groups, including Morgenstern and Cyrus, have published multiple papers validating the use of GIS as a platform for atmospheric modeling techniques for evaluating the health impacts of pollution (Morgenstern et al., 2007).

Another study demonstrated the utility of GIS to create geospatial maps of pollution concentration in urban areas (Matejcek, Engst, & Janour, 2006). Their article, however, is focused on computational kriging, or interpolation, techniques and the use of a LIDAR system to measure pollutants. Beelen et al. used GIS to determine the fraction of pollutants attributable to local, regional, and urban factors (Beelen, Hoek, Fischer, Brandt, & Brunekreef, 2007). They were able to develop a model that accounted for the majority of observed variation in outdoor pollution levels. Their methodology for attributing pollution to different factors could be used in future generations of this project to help separate local effects from regional or national ones. Others have also investigated kriging techniques and determined that averaging is a valid tool for finding concentrations at the residential level from regional data (Liao et al., 2006).

Health Impacts

The health impacts of diesel exhaust are very well described in the literature (Anselme et al., 2007; Riedl & Diaz-Sanchez, 2005; Sydbom et al., 2001; U.S. Environmental Protection Agency, 2002). Many studies have quantified the increased mortality and morbidity associated with high levels of atmospheric pollution. To cover even a significant fraction of them in this review would be impossible,

so I will examine only a small sample. The fundamental concept is clear though: the pollutants released by combustion are harmful and those harms can typically be quantified, modeled and predicted.

Any discussion of the health impacts of PM in the United States must begin with the EPA, which has classified PM as one of six “criteria pollutants”, which are closely monitored to track their effect on human health. The EPA has noted that there is a significant and well documented link between exposure to high levels of PM pollution in the air and respiratory disease. Additionally, there is increasing evidence that PM’s effect on cardiovascular health might be as great as its effect on the respiratory system (Künzli et al., 2005; Kunzli et al., 2000; Pope et al., 2002; Pope et al., 2004; U.S. Environmental Protection Agency, 2004).

Wong, Atkinson et al. (2002) studied the effects of air pollution on hospital admissions in London and Hong Kong. They hypothesized that pollution was associated with increased rates of admissions in two cities with vastly different population, climate and environmental characteristics. If true, this determination would lend strong support to the claim that pollution has negative impacts on health, regardless of the situation. By using seasonally-corrected Poisson regression, they were able to demonstrate significant correlations between pollutant levels and both cardiac and respiratory hospital admissions in both cities. This demonstrates the clear link between pollution and health in urban settings.

Similar studies demonstrated strong correlations between pollutants and health impacts in Caen, France (Glorennec & Monroux, 2007). The American Heart Association issued a statement for healthcare professionals that indicated their acceptance of multiple, peer-reviewed studies demonstrating short and long-term risks to cardiovascular health (Brook et al., 2004; Pope et al., 2004).

Andre Nel (2005), writing in *Science*, described several pathways by which particulates cause damage to lungs. The effect of pollution, especially sudden increases in pollutant levels, is well known to be particularly harmful to the elderly and those with chronic respiratory or cardiovascular conditions (known as the “harvesting” effect, hastening impending death). Schwartz looks at this effect and finds ample evidence of its effect on mortality (Schwartz, 2000).

Seasonality and humidity also appear to play a role in health impacts due to pollution. Wong and Atkinson observe higher mortality in Hong Kong’s winter and London’s summer. They hypothesize that the difference is due to the relatively low levels of humidity associated with those months. Others describe this phenomenon elsewhere in Western Europe. (Nawrot et al., 2007). Accounting for these effects will add a level of additional complexity that is probably beyond the scope of this project. Later versions may be able to take these variables into account, as humidity is recorded in most common meteorological databases.

A study that attempts to relate localized pollution sources to human health involves the effects of pollution from China’s rapidly developing Pearl River Delta on Hong Kong’s air quality (Xiao, Brajer, & Mead, 2006). The article attempts to determine whether Hong Kong’s air quality problems are, in any way, due to the presence of nearby Chinese industry. Xiao, Brajer and Mead use a very high-level statistical analysis to model the effects of Chinese pollution on Hong Kong, utilizing monitoring stations in both locations. Xiao, Brajer, and Mead also analyze Hong Kong’s effect on Pearl River pollution levels. Their project ultimately determines that the causality of air pollution runs both ways, “emphasizing the regional nature of air pollution”. They also determine that local pollution control measures would be, in this case, far more effective at reducing health burdens in Hong Kong than measures to reduce the industrial pollution in China. For the purposes of my project, this lends weight to the idea that local

factors are dominant when assessing the health burdens of air pollution, especially in the case of PM, which generally does not disperse as far as gaseous pollutants. The availability of a tool, such as I hope to create, would be of great use because it could be used to quantify the health burdens associated with local development and allow policies to mitigate the harms.

Computational modeling of health impacts from pollution has already been accomplished. The Environmental Benefits Mapping and Analysis Program (BenMAP) takes GIS maps of pollutant concentrations and overlays them on census data, to determine population exposure (Abt Associates, 2005). This tool is a GIS-based health impact modeling package that was developed for the EPA to use in modeling the effects of air-quality regulation. The exposure is then aggregated to determine the total health impacts of the pollution, which can be expressed in terms of number of cases or typical costs. The output format of ADMS is not structured in a way recognizable by BenMAP, and the conversion to an appropriate format, while feasible, is beyond the scope of this research project. I elect to employ a simpler, though less detailed method of health impact analysis that follows a similar framework to BenMAP. This mathematical method of health impact analysis, uses the methodology of Ostro, who applied dose-response functions for population exposure to PM₁₀ (Ostro, 2004). These functions will be applied in a fashion similar to that of Corbett, et al. who evaluated global mortality from ship emissions (Corbett et al., 2007). Ostro's technique was also used to conduct an evaluation of the health impacts of vehicle PM emissions in Sri Lanka (Chandrasiri, 2006).

I will focus on the health impacts of PM₁₀ for the purpose of this project for several reasons. First, the causality of PM₁₀'s health consequences is clear and well-documented. BenMAP focuses on PM (both 10 micron and 2.5 micron), which reinforces the impression that PM is a major health hazard. Similarly, the methods of Corbett and Ostro focus on the health impacts of PM. Additionally, gaseous

pollutants such as NO_x, SO_x and CO disperse over great distances and so causality of any health impacts resulting from them becomes fraught with complications. When the health impacts of freight movement in California were examined, the overwhelming focus was on PM and Ozone pollution, which reinforces the message that PM is worthy of the primary focus in health impacts (Tran, 2006). Finally, the structural components of this model can be described using only one pollutant, since additional pollutants can be evaluated using the same techniques. Since this thesis is intended to describe a framework for future work, structural consistency is of more importance than comprehensive health impact quantification. Future versions of this model can include additional pollutants using similar methodology.

Policy Perspectives

Several authors have written about the concept of policy modeling, based along the same framework as I am utilizing. Rabl et al. (2007) discuss a policy model based along an emission-dispersion-dose/response-monetary valuation model. The difference between Rabl's work and this thesis is the attempt to consolidate all the tools into a single analytical process. While there is obvious value in monetizing the health impacts of pollution, the methods by which this is done are open to argument. From the standpoint of informing local stakeholders and contributing to the discussion of policy options, data stated in terms of health risk may be of more use than data stated in financial terms.

The Network for Environmental Risk Assessment and Management (NERAM) issued a conference paper with 10 directions for future policy research (Institute for Risk Research, 2008). This paper called for, among other things, better involvement of interested stakeholders and more effective

analysis of targeted interventions. My model will be helpful on both counts. A single, more inclusive model will allow health analyses to be conducted more quickly with less need for novel research and model creation. This will allow a broad spectrum of communities to analyze future development plans and project the effects of pollution-control policies. My model will also allow changes in economic activity, such as increased truck activity, a new freight facility or expansion of residential development, to be more quickly and easily evaluated for their impact on pollution issues.

This project has maintained a focus on the principle of empowering policy makers to make good decisions. A large part of why air pollution and global climate change are issues is that they are difficult to account for in economic transactions. Pollution is the classic example of an economic externality. The ultimate goal of this tool is to allow the health effects of pollution to be brought into decision making processes. With an account of the expected health impacts, policy makers can either attempt to monetize and compare directly against the economic impacts of a plan or use multi-goal analysis and consider the tradeoff between development and health. The importance of this concept is reinforced by research highlighting the health disparities that exist across communities, particularly as it comes to respiratory diseases and environmental factors.

Asthma's disproportionate impact on certain communities has been repeatedly noted in research. These disparities are largely a result of environmental factors, including pollution from motor vehicles near to homes (Shanawani, 2006). The model I am attempting to create will hopefully be able to account for communities that already suffer from high burdens of disease, assuming that such information is available in geographically defined form. Even if it cannot be directly included in the model, the availability of a tool to allow better prediction of pollutant spread will allow affected communities to make a case for reduction of pollution-intensive activities near their homes and ensure

that health costs are part of the discussion when considering economic policies. Others have also examined the impact of pollution on disadvantaged communities, concurring with the finding that air pollution disproportionately affects poor communities. They note and examine the relationship between proximity to pollution sources, such as highways, and property values (Bae et al., 2007).

Summary

The subject of pollution, and its health impacts, has been widely studied (Clean Air Task Force, 2005). In no way do I wish to present this review as a comprehensive account of all literature in the field. As it stands, it merely suffices to set the theoretical groundwork for my proposed thesis.

The first stage of the pollution cycle, emission, is very well researched and the necessary information for this thesis is readily available. Emissions factors have been well researched and are available from several sources. The validity of GIS as an analytic tool for pollution problems is well known. There are a variety of ways by which an emissions map may be drawn and emissions factors applied.

The dispersion stage of the pollution cycle presents more challenges. Ultimately, my review of literature encourages me to take the more expedient decision as opposed to the more accurate one. Atmospheric dispersion models are available, but often require specialized knowledge to properly access. They are also often expensive to acquire. The purpose of this thesis is to demonstrate the analytic framework for predicting health impacts from freight transport. If this thesis can create such a framework, it would be feasible to alter future versions to utilize other models of atmospheric dispersion. In the meantime, ADMS represents a far simpler and more available method of predicting

pollutant behavior. Additionally, careful selection of location of test cases may allow for us to utilize the analytic framework under conditions similar to those assumed in the Gaussian model.

The health impacts modeling, step 3, appears to have a simple solution as well. I will compile dose-response functions and perform the calculations in an Excel spreadsheet.

Finally, many critical policy implications were made very clear by this review. While my approach is not novel, the framework will define how it can be generalized and used in many situations. This becomes critical when we realize that in many cases, the health impacts of pollution are felt most heavily by communities already suffering from economic hardship. Much of the problem associated with pollution is that the harms of pollution are hard to account for in economic transactions. While it is possible to examine them, it often takes specialized expertise and techniques to do so. The availability of a more easily accessible tool will allow greater numbers of communities or actors to take environmental costs into account when evaluating policy actions. My hope is that by improving the information that surrounds these decisions, life for everyone, particularly disadvantaged communities, can be improved.

Methodology

Emissions Characterization

Quantification of Emissions

The first step in estimating health impacts from diesel emissions is to quantify and spatially locate the emissions. GIS software has been demonstrated to be an effective tool for spatially locating pollutant concentrations based on both Air Quality Measurement (AQM) data (Liao et al., 2006) and predictive modeling (Mindell & Barrowcliffe, 2005). ArcGIS 9.x (ESRI Inc., 2007) is a widely available commercial GIS software package that has the capability of accepting a wide variety of data formats for import and export functions. Additionally, ArcGIS has a long history of use in the environmental sciences.

Spatial location of emissions requires two main inputs: the quantity of emissions and their location. Vehicles on a road are typically modeled as a line source and the quantity of emissions can be determined by multiplying the number of vehicles by a per-vehicle emission factor (Winebrake et al., 2008). In line source dispersion modeling, the quantity of interest is the amount of emissions per unit of length per time period. PM_{10} concentrations are expressed in micrograms per cubic meter of air and emissions measurements are taken in units of grams of PM. The net emission value can be determined as follows:

$$Emissions \left(\frac{g \text{ } PM_{10} \text{ emissions}}{km \times second} \right) = \frac{Vehicles}{Day} \times \frac{1Day}{86400 \text{ seconds}} \times \frac{g \text{ } PM_{10} \text{ emissions}}{vehicle_km} \quad (1)$$

The optimal method for determining the number of vehicles per day on a given segment of road is a direct count of traffic. In many cases direct counts are not available and estimation, sampling or modeling is necessary. In the U.S., most state departments of transportation keep these data in publicly available archives; though in many cases the data are restricted to major highways only. If traffic count data are not available, counts can be made independently by direct or instrumental observation. Planning documents, such as traffic analyses or development permits, may be able to provide vehicle flow information for individual projects or locales.

Selection of the type of vehicles to examine will be determined largely by the pollutant species under study and the emissions characteristics of the vehicles in the study area. In general, diesel engines are a concern to public health, due to high emissions of NO_x and PM; in most cases diesels emit more of these pollutants than comparable gasoline engines. Diesel engines have been repeatedly singled out for study by sources in public health and air quality literature (Abu-Allaban et al., 2003; Anselme et al., 2007; Clean Air Task Force, 2005; Forkenbrock, 2001; Riedl & Diaz-Sanchez, 2005; Samet, Dominici et al., 2000; Samet, Zeger et al., 2000; Sydbom et al., 2001).

For general purposes, the emissions factors used in the GIFT model (Winebrake et al., 2008) represent average values representative of many types of U.S. freight trucks. For PM₁₀, the average value was 0.237 grams PM₁₀ per truck*mile. This value was obtained from the Greenhouse Regulated Emissions and Energy use in Transportation (GREET) model (Wang M.Q., 2001). This matches the figure derived by linear interpolation between 2002 and 2010 diesel combination freight truck PM₁₀ emission factors given in Appendix B of *Assessing the Effects of Freight Movement on Air Quality at the National and Regional Level* (FHWA, 2005).

If additional pollutants, beyond PM_{10} , are to be studied, the above methodology can be repeated as needed, to determine all appropriate emissions factors. In particular, evaluation of $PM_{2.5}$ would be of particular interest to health policy analysts since it, like PM_{10} , is strongly associated with health problems. I chose to omit $PM_{2.5}$ from this analysis for two reasons. The primary reason is that ADMS does not include dispersion algorithms for $PM_{2.5}$. Additionally, much of the effect of $PM_{2.5}$ is captured in the analysis of PM_{10} , since the former is a subset of the latter. The ratio of $PM_{2.5}$ to PM_{10} is strongly influenced by factors such as road dust, brake wear and tire ablation. Several sources present differing figures regarding the fraction of PM_{10} that is $PM_{2.5}$, ranging from 50 to 80%.

Spatial Location

Emissions are spatially located by selecting routes to study in the ArcGIS user interface, using the ADMS route tracing tool. The user manually describes the route using the mouse, clicking on a starting point and again at each vertex along the route. This is, unfortunately, a rather cumbersome method of describing routes. It requires a significant amount of time, if there are many routes in the case being studied, and the routes themselves cannot perfectly reproduce the road contours.

Spatial location of emissions is a necessary step in dispersion modeling and is included in every dispersion modeling software package. Locating the emissions from on-road sources will be accomplished by utilizing maps of road networks. To define a route, the user will display a map of the scenario location and trace over freight routes using the tracing tool. This technique requires that the user have access to freight routes and traffic volume data, if conducting analysis on existing freight

routes, or proposed changes to traffic routes and volumes, for prospective studies. The traced route is converted into a polyline shapefile, which becomes the line along which pollutants are emitted.

Dispersion

The next step in the model is dispersion. Once pollutants, such as PM₁₀, are emitted, they disperse through the atmosphere, spreading out from their point of emission. A fraction of the emitted pollutants are absorbed or deposited as they contact surfaces, while others are removed by chemical reactions in the atmosphere. This fraction varies depending on atmospheric conditions and pollutant characteristics. The process of atmospheric dispersion has been studied in great detail. In general, concentrations of pollutants follow a Gaussian distribution (Masters, 1997), though the dispersion behavior will be significantly modified by wind, temperature, humidity and other atmospheric conditions.

On-road vehicle emissions are typically modeled as line sources (Masters, 1997; Nagendra & Khare, 2002), which approximates the effects of many vehicles moving along a road as a line; emitting a defined amount of pollution, per unit of time, along its length. Many dispersion models, ADMS included, can also model point or area sources. Point sources are stationary emitters, such as a factory or power plant. Area sources emit a defined amount of pollutants per unit of area and are often used to approximate urban or suburban areas, which have low levels of pollution emitted by vehicles and small point sources dispersed over a relatively large area. The following equation is the basic estimation of the concentration of pollutant C at distance x from the road (Masters, 1997).

$$C(x) = \frac{2q}{\sqrt{2\pi} \sigma_z u} \quad (2)$$

Where q is the quantity of pollutant emitted per unit of road; σ_z is a dispersion coefficient which is dependent on x ; and, u is prevailing wind speed.

For the purposes of this thesis, I will focus solely on line sources. This is primarily due to data availability and research focus; roads often pass close to populated areas and so the freight traffic on those roads potentially pose a public health risk. Similar methodology could be used to include point and area sources within this analytic framework. Freight transfer facilities can be modeled as point or area sources, depending on the size of the facility relative to the area being analyzed. Modeling urban or industrial locations as an area source would likely be a helpful addition to the model, but this requires significantly more data regarding emissions at multiple points in a production cycle. This data may not be publicly available. As the case study will demonstrate, it is likely that these areas are significant contributors to PM pollution and future research should seek to characterize their impact on public health.

One advantage of ADMS is that it naturally integrates with ArcGIS and facilitates the interface between emissions characterization and dispersion. Once the route is traced in the ArcGIS window, the route is immediately imported into the ADMS working libraries and levels of activity can be set. Levels of activity can be defined in terms of an emissions factor for a given segment (g of pollutant/km*second, calculated using equation (1) from above), in ADMS, can be derived by entering the number of vehicles per hour on the given segment of road and selecting a pre-determined emissions factor.

The next steps set the dispersion environment; the background levels of pollutants and meteorological conditions. Background pollutant concentration is a necessary component of dispersion

modeling. In the U.S., the EPA maintains records of pollutant levels from a wide network of monitoring sites, including many operated by state and local environmental agencies, at www.epa.gov/air/data/geosel.html (U.S. Environmental Protection Agency, 2007b). The coverage of this monitoring network is not entirely complete. Some states do not measure all pollutants; for example, New York tracks PM₁₀ at only a single station outside of New York city. Similarly, Chicago has only four PM₁₀ monitoring stations, primarily clustered around the south-central part of the city. This gives incomplete (or absent) coverage of many parts of the nation and obliges the estimation of background pollutant concentrations in many cases.

Meteorological data can be found from a variety of sources, including the National Climatic Data Center (www.ncdc.noaa.gov) and the National Oceanic and Atmospheric Administration (www.weather.gov). Month-by-month averages for most major U.S. metropolitan areas can be found at www.weatherexplained.com. The most critical value for determining dispersion characteristics is wind speed and direction. Ideally, the dispersion model will utilize hour-by-hour, detailed measurements of weather activity, though average prevailing winds may be acceptable as well. Other critical features are temperature, cloudiness, atmospheric stability, surface roughness and Monin-Obukhov length (a measure of turbulence at varying levels of the atmosphere). Some of these values are available from meteorological databases, others (Monin-Obukhov length and surface roughness in particular) are taken from the suggested urban defaults in ADMS.

Ultimately, pollutant concentration data and meteorological conditions are available from a variety of sources. There is a significant challenge in locating and accessing these data. Much of U.S. weather data are kept in the NetCDF file format, which requires a special software library to access. Additionally, they are noted using terms of meteorological art that are difficult for non-experts (such as

myself) to comprehend. Since the primary problem appears to be data accessibility, rather than data availability, it is possible that future versions of this tool could programmatically automate extraction of relevant weather information. Without the benefit of future work, simpler sources such as www.weatherexplained.com (which displays aggregated monthly averages rather than detailed hour-by-hour data) become more feasible alternatives to hour-by-hour data. Additionally, utilizing detailed, hour-by-hour data dramatically increases the computational requirements of the dispersion model.

Utilizing the given inputs, the dispersion model simulates the behavior of pollutants, including motion through the air, settling onto surfaces and removal by chemical or physical deposition. Output, for most models, is a grid of points that covers the extent of the scenario area and contains a pollutant value for each location. These values can be applied to maps of population to calculate health impacts.

Health Impact

Health impact calculations are accomplished using the method described in the World Health Organization's *Environmental Burdens of Disease* (Ostro, 2004). This technique calculates mortality from cardiopulmonary disease and lung cancer as a result of exposure to particulate matter.

$$E_C = AF \times B \times P \quad (3)$$

$$AF = \frac{RR - 1}{RR} \quad (4)$$

$$RR_{log-linear} = \left(\frac{X + 1}{X_0 + 1} \right)^\beta \quad (5)$$

$$RR_{linear} = e^{\beta(X - X_0)} \quad (6)$$

Where E_C is the expected number of deaths from disease C (e.g. cardiopulmonary disease or lung cancer), B is the baseline population incidence rate of disease C (deaths per 1,000 people), X_0 and X are the background concentration of and post-dispersion concentration of particulate matter in micrograms per cubic meter, P is the population exposed to the change in PM exposure, AF is the affected fraction of people from the pollutant, RR is the relative risk ratio of population with and without the “additional” pollution and β is a calculated constant, determined by regression of empirical dose-response data (Table 1). This methodology has been applied to several health impact analyses of emissions from freight transport, notably an assessment of mortality from global shipping (Corbett et al., 2007).

Table 1 - Beta Coefficients for Cardiopulmonary Disease and Lung Cancer. High and low values are the maximum and minimum extent of the 95% confidence interval. Source: Pope (2002) cited in Ostro (2004)

	Cardiopulmonary	Lung and Bronch Cancer
Log-Linear		
Beta	0.15515	0.23218
Beta Low	0.0562	0.08563
Beta High	0.2541	0.37873
Linear		
Beta	0.00893	0.01267
Beta Low	0.00322	0.00432
Beta High	0.01464	0.02102

It is important to note that this method determines mortality from *changes* in PM levels as opposed to total exposure. This indicates that it is of great importance to determine a background level of pollution in absence of the freight activity being examined, since the background levels affect dispersion activity as well as the magnitude of health impacts. It is also important to note that

cardiopulmonary diseases and lung cancer are not the only pathologies arising from exposure to PM, so this technique may somewhat underestimate total population health impacts. A final important characteristic of this method of health impact calculation is that the above equations and β values apply only to the segment of a population above 30 years of age. Any population figures used to determine mortality must be corrected to reflect the fraction of population over 30.

A question of particular importance is how to accurately determine the population exposed to changes in PM. In the U.S., the smallest distinct unit of census data is the census “block”. Often coinciding with a street block, a census block usually contains less than 1,000 (and often less than 100) people. Census block data is included with ESRI’s *StreetMap 2007*. Other nations typically record similar data, though often at a less detailed scale. Population exposure can be done in several ways, depending on how the population data is stored. If populations are recorded in association with polygonal census blocks, then the fraction of each block falling into each predicted pollution grid square can be calculated and the pollutant levels of the grid square can be applied to that fraction of the population. This approach requires the dispersion model to output a grid reflecting pollutant concentration (which most, if not all, models will do) then kriging, or interpolating, the concentrations of nearby cells to determine the concentration of pollutants that affect a given census tract (or subunit of the tract). This technique has been demonstrated to be effective in literature (Matejicek et al., 2006), but is computationally and mathematically intensive and beyond the scope of this research.

Alternatively, if the resolution on the population data is fine enough, an approximation can be made based on the centroids of census blocks. Many pollutant dispersion packages, including ADMS, allow pollutant levels to be calculated at specific points, rather than (or in addition to) a grid. In this case, pollutant levels can be calculated for the centroid of each census block, and the pollutant

concentrations for that centroid can be applied to the population of that entire block. This assumes that the pollutant concentration will be constant over the entire census block. Most census blocks with a significant population are very small; often they are single city blocks, significantly less than a kilometer on a side. PM concentration levels drop off very sharply in the 200-300 meters closest to ground-level sources (such as vehicles), but after that distance, remain approximately constant (Zhu et al., 2002). Accordingly, this study assumes that in census blocks removed from highways by half a kilometer or more the PM concentration will not vary significantly across the area of the block. This assumption may not hold for blocks very close to highways, but as will be discussed later, the overwhelming majority of population in this study (and likely, in most studies of highway PM pollution) is well removed from the immediate vicinity of highways. This method is likely to be slightly less accurate than fractional calculation based on polygon areas, but it is significantly simpler and reduces both computational burden as well as the requirements on the operator.

The optimal approach to use depends on the level of programming expertise of the operator, the amount of computing resources available and the format of population data. In most cases, the centroid method is simpler, though the polygon-kriging method is likely to be more accurate. Future work should compare the results of the two methods to determine how comparable they are.

The output of the health impact calculations are expected mortalities from cardiopulmonary disease and lung cancer, which can be summed across all census blocks to yield a total health impact, or examined spatially to gain a sense of the spatial characteristics. One potential application would be to graphically project it onto the original map of the area under study, in order to spatially locate the areas worst-hit by health impacts.

Summary

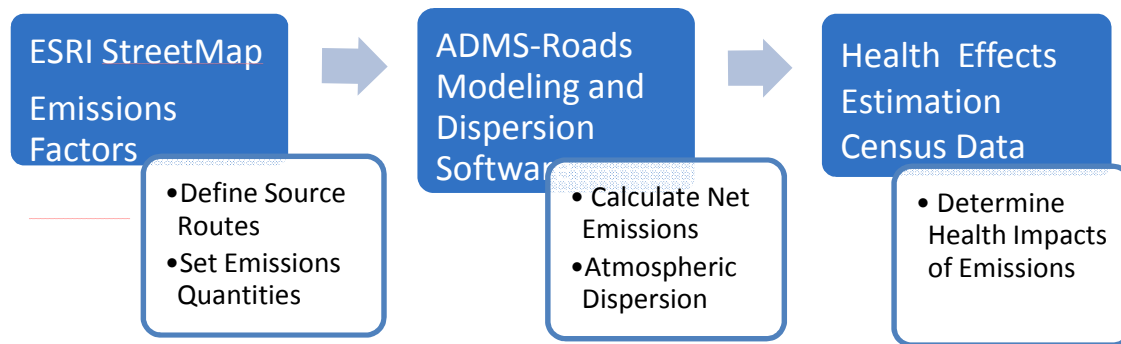


Figure 1 An operational diagram of the analytic framework. The arrows represent scripts used to direct the flow of data. See Appendix A for details regarding integration of units and data flow.

The methods described above each allow for evaluation of one “step” in the analytical process required to evaluate the health impacts of diesel exhaust from on-road trucks. It is important to realize that multiple techniques exist for each step in this process. The steps utilized in this thesis represent the best practices validated by literature and available to the author (See: Literature Review), however they may not be the optimal approach for these problems. It may be possible to modify substitute alternative methodologies in any of the steps of this framework; though doing so may require more robust methods of data exchange and process integration (See: Future Work).

Development

The model described in preceding sections was demonstrated by evaluating a representative test case. The site was selected based on the availability of input data (meteorology and PM₁₀ background concentration), sufficient population and major highways that pass near population areas. These characteristics would make it likely that there would be measurable health impacts from freight transport.

Californian cities lend themselves to this sort of analysis. Due to long standing recognition of the health problems caused by pollution, California has a very thorough network of pollution monitoring stations all of which report data to the U.S. EPA's AirData online database. California also is heavily populated with several major metropolitan areas, as well as significant freight activity; the result of several major ports (Los Angeles/Long Beach, Oakland, San Diego). Sacramento was chosen as the case study city. Sacramento shares all of the above characteristics with other California cities and the major interstate highways pass through the central city (Figure 1,2), which indicates there is a significant potential for exposure of population to diesel particulates.

In many situations, policy makers would like to test the hypothesis that a given set of freight transport activities poses a significant health hazard to their communities. The analytic framework described by this thesis was designed for answering this question and this case study demonstrates how this would happen.

Sacramento has eight PM₁₀ monitors at five locations (some locations have multiple sensor types at the same position). For this study, the 2007 annual average for each station was used, which produced a mean of 21 µg/m³ (σ=2.6).

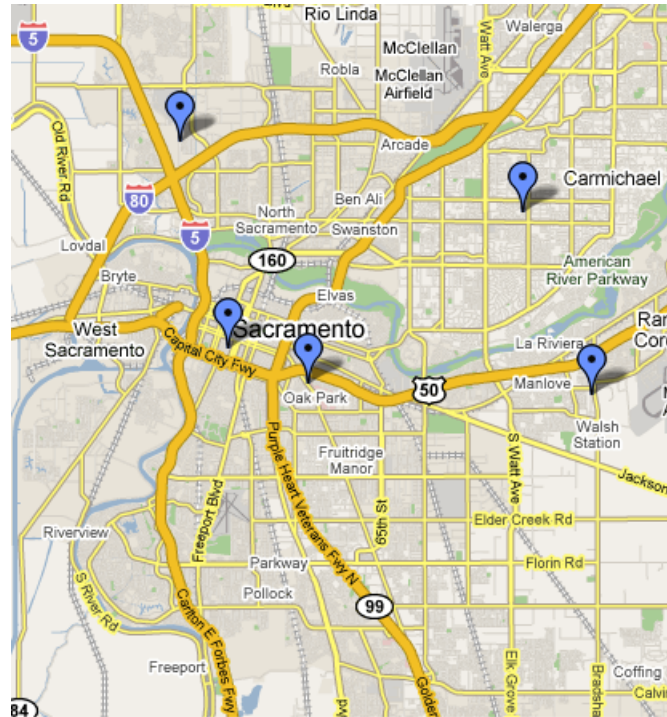


Figure 2 - EPA PM₁₀ monitoring sites in Sacramento, CA. Note that the northern part of the city is more thoroughly covered than the southern part. (Source: GoogleMaps, EPA 2008)

In the Sacramento case study, truck counts were obtained from the report *2006 Annual Average Daily Truck Traffic on the California Highway System* (California Department of Transportation, 2007). This report gives truck traffic counts for all roads in the state highway system. Entries for Sacramento County were extracted into an Excel spreadsheet. Many highways had similar counts at closely spaced intervals, resulting in redundant data. Representative estimates of vehicle flow were created by averaging traffic volumes across contiguous sections of highway that had similar (within 10%) traffic volumes. ADMS is limited to computing pollutant concentrations for 10,000 points, which limits the

area that can be studied at one time when using the centroid approach to health impact characterization (similarly, it would limit the resolution of a concentration grid for the polygon-kriging approach). To avoid exceeding the 10,000 point threshold, segments outside of densely populated areas were excluded on the assumption that there would be comparatively few health impacts in sparsely populated areas. In general, this exclusion zone coincided with Sacramento city limits, though parts of some incorporated suburbs (North Highlands, Fair Oaks, Carmichael and West Sacramento) were included. Future versions of this analytical framework should seek to expand the number of points that can be modeled, making this restriction unnecessary.

In all, 19 distinct segments of highway were found in the core Sacramento metropolitan area (Figure 3). These were traced using the ADMS trace route tool and exported to ADMS. The traffic volume report broke truck traffic into bins determined by the number of axles. The Department of Transportation limited two axle trucks to those with more than four tires, in order to exclude pickups and SUV's from being counted with heavy-duty vehicles. The two-axle category was further subdivided into diesel and gasoline powered categories according to the diesel fraction given in the *Transportation Energy Data Book - #26* (Oak Ridge National Laboratory, 2007). Trucks with three or more axles were classified as heavy duty and assumed to be diesel-powered.

The spatial location of emissions was determined by referring to road maps of the region taken from ESRI's *Streetmap 2007* (ESRI, Inc.). Spatial locations were taken from the *2006 Annual Average Daily Truck Traffic on the California Highway System* and correlated to street name fields from *Streetmap 2007* and visually double-checked using Google Maps.

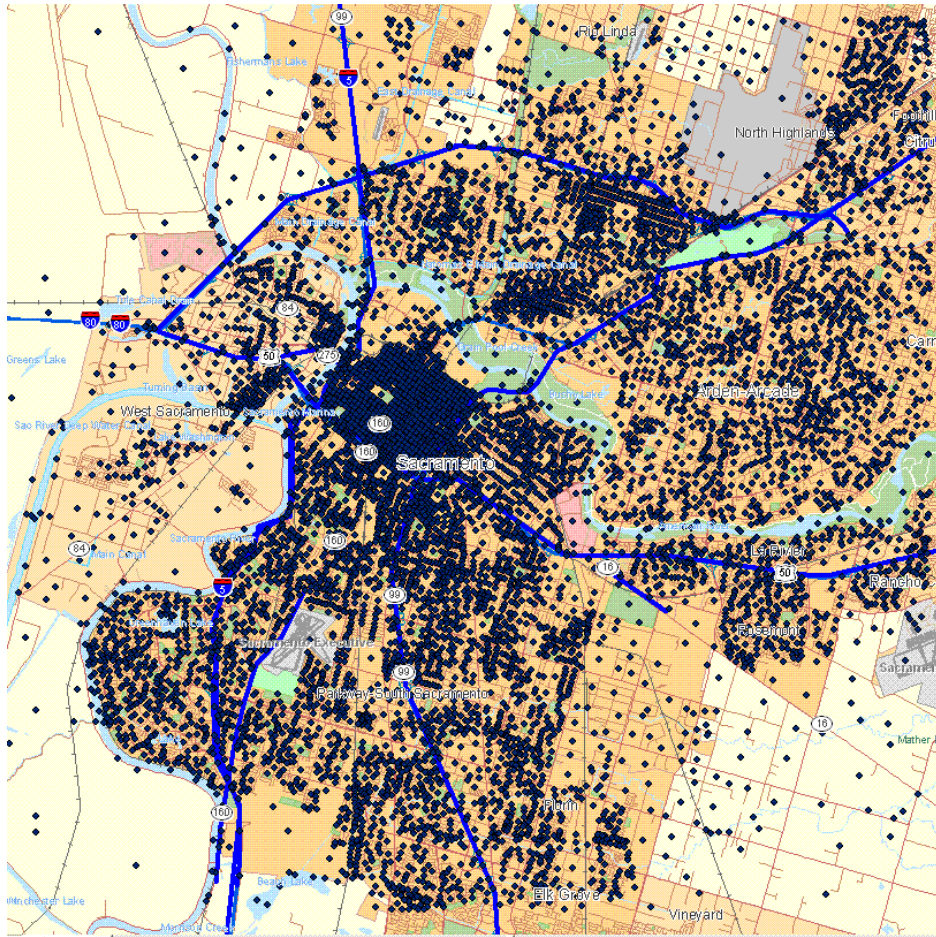


Figure 3 Map of Sacramento with Census block centroids. Source: ESRI StreetMap 2007



Figure 4 - ADMS Freight Routes

Spatial locations were entered into ADMS using the ADMS-Roads ArcGIS Link tool, which provided a cursor with which to trace routes on a map. The routes were then imported into ADMS and emissions values from above were input using the ADMS interface.

Table 2 - Truck traffic in the Sacramento Area. Source: Caltrans (2006)

	<i>Light Duty</i>	<i>Heavy Duty</i>	<i>Diesel</i>	
	<i>Trucks</i>	<i>Trucks</i>	<i>Trucks</i>	<i>g PM10/km*s</i>
Description	(trucks/hour)	(trucks/hour)	(trucks/ hour)	
I5 San Joaquin to city limit	135.4	449.8	483.6	0.01978
I5 city limit to downtown	162.5	523.1	563.8	0.023066
I5 downtown to I80	159.5	435.6	475.5	0.019456
I5, I80 to county line	143.8	340.2	376.1	0.015390
Rte 16, 5/50 junct. to Florin/Perkins Rd	15.5	34.3	38.2	0.001562
I50, Sunrise to I99	166.6	175	216.7	0.008865
I50, I99 to County line	110.4	147.1	174.7	0.007147
I51 (Biz80)	195.8	157.1	206.0	0.008430
I80, I5 vicinity	120.8	226.0	256.3	0.010484
I80, I51 Vicinity	113.3	262.1	290.4	0.01188
I80, Greenback	122.9	261.2	291.9	0.011944
I99	133.3	277.9	311.3	0.012735
Rte 160 In-City	67.9	25.9	42.8	0.001752
Rte 244 (Auburn Blvd off-ramp from I80)	51.0	76.5	89.2	0.003650
Rte 275 (Capital Mall)	4.2	1.7	2.8	0.000112

The routes to study are given in Table 2. The right hand column is derived using equation (1) and the emissions factors from GREET, as described in Methodology. These emission factors were manually entered into ADMS¹. Weather data was taken from www.weatherexplained.com, which had yearly averages for Sacramento, last updated in 2001. Wind speed and direction information were taken from monthly average prevailing winds (210°, 3.5 meters/second), which are an estimate of wind behavior. More granular data, such as weekly or hourly figures would be ideal for this analysis but were not available in an accessible format. Average temperature and cloudiness were taken from the same source. Monin-Obukhov length and boundary layer height were left at ADMS default, 30m and 800m respectively. Surface roughness was set to 1 meter, which is the value recommended for urban areas by

¹ These values were ultimately about 10% higher than those predicted using the built-in ADMS emission factor calculator, which is based on European data from 2003.

the ADMS user's manual. Ideally, three-dimensional characteristics of major buildings would be added to the dispersion model, but the process for doing this is beyond the author's grasp.

Population values, in the form of census block centroids, were taken from ESRI Streetmaps 2007. The ID and coordinates were selected and copied to a new file, and a Z coordinate (set to zero) was added to each location. This file was named with a *.asp extension and included in the ADMS working directory. The model was run and the resulting comma separated value text file was merged back into the list of census block centroids. The merge was verified by subtracting the numeric ID value from the ADMS output from the numeric ID value from the population file. All differences were zero, indicating that the merge was completed successfully.

A critical component of Ostro's health impact analysis methodology is establishing a "baseline" level of PM exposure. Ostro's method, ideally, would use past air quality monitor data in order to show the effect of the policy or actions under study. Since I am considering the health impact of trucks in the status quo, the air quality monitoring data from the Sacramento region will include the effects of the activity under study; there is no meaningful way to measure what the PM₁₀ concentration would be if there were no trucks on the highway. Because the baseline concentration affects both the dispersion behavior and health impacts in a non-linear fashion, it is important to be able to approximate a baseline pollutant concentration that reflects the absence of the activity under study. Since there is no way to directly record what Sacramento's air quality would be like if there were no trucks on the highway, I am obligated to approximate this value.

I chose two methods of approximation. Case 1 used the monitor values, 21 µg / m³ (U.S. Environmental Protection Agency, 2007b) as the baseline pollutant concentration for the dispersion

model. The dispersion simulation would then determine the additional contribution of diesel freight trucks above this baseline. This contribution was subtracted from the observed value to determine the implicit baseline of PM₁₀ pollution in absence of the modeled activity. This set of assumptions is “Case 1”.

Another approach to estimating baseline PM is to approximate the amount of PM₁₀ in Sacramento that would result from truck activity, subtract that from the observed values and use that as a baseline. EPA mobile source data indicates that particulate matter from on-road diesel engines account for approximately 5.6% of anthropogenic PM₁₀ emissions (U.S. Environmental Protection Agency, 2003). It does not appear that a recent source apportionment has been done for PM₁₀ in the Sacramento area, however Motallebi, in examining winter time PM₁₀ sources states:

First, the source apportionment results indicate that primary motor vehicle exhaust and wood smoke are significant sources of both PM sub(2.5) and PM sub(10) in winter. Second, nitrates, secondarily formed as a result of motor-vehicle and other sources of nitrogen oxide (NO sub(x)), are another principal cause of the high PM sub(2.5) and PM sub(10) levels during the winter months. Third, fugitive dust, whether it is resuspended soil and dust or agricultural tillage, is not the major contributor to peak winter PM sub(2.5) and PM sub(10) levels in the Sacramento area. (Motallebi, 1999)

No similar source apportionment of year-round data was available, however, a study of the size and composition of PM₁₀ at several Northern California locations reported that overall PM₁₀ concentrations were significantly lower at a location that was relatively close to agricultural areas, but some 120km removed from the nearest metropolitan area than similar sites in either metropolitan or agricultural areas. This implies, though the authors of the study did not explicitly state, that airborne transport of dust, in the absence of severe wind, is a relatively local phenomenon. The parts of Sacramento that I examine in this case study are well removed (>50km) from any significant agricultural activity and we can assume that Motallebi’s conclusion that suspended dust is not the major contributor to Sacramento’s urban PM₁₀. This conclusion should be tested by an explicit source apportionment of Sacramento’s PM₁₀, using methodology established in literature (Chow et al., 1992; Furusjo, Sternbeck,

& Cousins, 2007). Subtracting 5.6% of $21 \mu\text{g} / \text{m}^3$ leaves a baseline pollutant concentration of approximately $19.5 \mu\text{g} / \text{m}^3$. Case 2 will assume a baseline concentration of $19.5 \mu\text{g}/\text{m}^3$ and add truck activity to that.

The results of the dispersion indicated that the overwhelming majority of census block centroids experiences less than a $.1 \mu\text{g}/\text{m}^3$ increase in PM_{10} concentrations. The results and baseline assumptions for each case are represented in Figure 4.

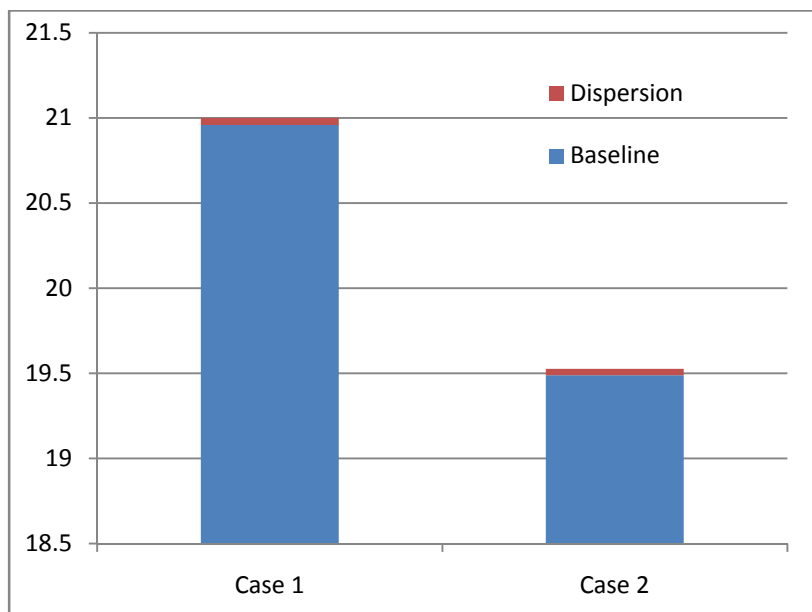


Figure 5 - Concentration of PM10 in the three case studies.

Results

Table 3 - Projected Mortality from PM₁₀ emissions from on-highway trucks in Sacramento, CA

PM Mortality from Diesel Truck Traffic in Sacramento, CA							
Case		Beta		Cardio-pulmonary, Log-Linear	Respiratory Cancer, Log-Linear	Cardio-pulmonary, Linear	Respirator Cancer, Linear
Case 1		Mid		1.16	1.74	0.73	1.03
		Low		0.42	0.64	0.26	0.35
		High		1.90	2.83	1.19	1.71
Case 2		Mid		1.24	1.85	0.75	1.06
		Low		0.45	0.68	0.27	0.36
		High		2.03	3.02	1.22	1.75

As shown in Table 3, the model indicated that the mortality associated with highway diesel PM₁₀ emissions, in both cases 1 and 2, was approximately 3 deaths per year (95% CI 1-5). Both cases produced similar results; Case 2's slightly higher predicted mortality is likely due to the fact that Case 1's baseline is at a higher level, which puts it farther "along" the logarithmic dose-response curve. The logarithmic dose-response function is such that an equal change in PM₁₀ will result in different expected mortalities depending on where the baseline is set. Case 2's higher mortality reflects the lower baseline for this case.

At first glance, the mortality predictions seem unexpectedly low. For comparison, the California Air Resources Board commissioned a study of the health impacts of goods movement, which predominantly focused on PM as the mediator of health impacts. This study determined that California suffers approximately 1500 additional deaths per year from the operation of trucks within the state (Tran, 2006). If we were to assume that Sacramento suffers deaths at the same rate as the rest of the

state (Equation 7) and that trucks are the dominant source of PM in central Sacramento, then one would expect approximately 39 deaths in our study area.

$$Expected\ Mortality_{Sacramento} = Expected\ Mortality_{California} \times \frac{Population_{Sacramento}}{Population_{California}} \quad (7)$$

This is an extremely rough approximation, but it at serves to set a boundary on the magnitude of expected health impacts. With this in mind, the result of this analysis is almost within an order of magnitude of those predicted from by CARB. Several reasons present themselves as explanations for the comparative lack of health effects noted; these will be discussed shortly.

In light of the unexpected results, comparison to established case studies could help determine whether the methodology of this thesis is fundamentally flawed. Unfortunately, few authors have published studies comparable to this one.

A study of the health impacts of diesel vehicles in Colombo, Sri Lanka using Ostro's health impact methodology determined that an increase of $33.83 \mu\text{g} / \text{m}^3$ caused between 550 and 712 (575 average) deaths per year, from a population of 337,000 (Chandrasiri, 2006). To confirm the results, I applied the health impact methodology used in this thesis to the population and PM_{10} changes described by Chandrasiri. My results indicated between 280 and 1250 deaths (764 average) based on the same data. Chandrasiri does not fully explain the techniques used to arrive at the $33.83 \mu\text{g} / \text{m}^3$ estimate, nor whether it is evenly distributed across his study area. Both techniques arrived at similar results, which support the claim that the application of Ostro's methodology described in this thesis is generally sound.

Further confirmation can be found by looking at the results of Corbett et. al., (2007), who examined worldwide mortality from shipping. That analysis observed a global increase of 0-2 $\mu\text{g} / \text{m}^3$ PM due to shipping, with the higher values overwhelmingly located over oceans or near major ports and shipping lines. Values inland typically increased by less than 0.5 $\mu\text{g} / \text{m}^3$. This is roughly analogous (though somewhat greater) to the increase in PM₁₀ concentration reported by the ADMS dispersion in this case study. The average global mortality from this increase (values varied depending on the emission routes and dispersion methodology) was approximately 42,000 (Corbett et al., 2007). This represents approximately 6.5 per million of the world's population. The results of this thesis, approximately 3 deaths from a population of 753,000 in the study area, represents 4 per million of the city's population. One would expect ship emissions to have a greater affect on world mortality due to the large numbers of people who live near the ocean, in major port cities. Additionally, the higher average PM concentration increase would be expected to result in greater mortality. Again the methodology of this thesis appears to produce results comparable to similar studies in literature.

Examination of similar studies in literature appears to confirm that the results obtained in this project are approximately what would be expected from the scenario presented. The perception that the results of the case study are erroneously low may be unwarranted. Several reasons exist why this study would demonstrate a relatively low health impact from trucks on the highway and lead to uncertainty in the result:

- 1) The analysis captures trucks operating at highway speeds, which assumes steady operation.

During most times of day, this assumption is generally valid. At several points, however, traffic becomes congested and driving patterns shift to stop-and-go. These patterns emit significantly more pollutants, .75 g/mile stop and go driving (Ubanwa et al., 2003) than steady state driving,

.24 g/mile (Wang, 2008). This would cause an underestimation of true impacts of truck PM emissions. The methodology presented utilizes a single emissions factor for each segment of road; future versions may need to apply a time-dependent emissions factor to reflect different driving patterns at different times of day. Alternatively, if an accurate mean could be determined, that could be used to approximate the effects of intermittent driving.

- 2) Off-highway activity. A significant amount of freight activity occurs on the surface streets of Sacramento, due to both local pick-up and delivery activity as well as through traffic to the suburbs and small towns in the surrounding area. These activities, by necessity, force trucks into an intermittent driving cycle and often directly through high-density residential areas. These activities are outside of the scope of this project, but may be a significant public health risk. This effect would cause an underestimation of both the emissions and the health impacts of truck PM₁₀ emissions.
- 3) Mortality vs. morbidity. This study examines only mortality since morbidity quantification is a more complex analysis and requires significantly more data. Due to emissions reduction policies in the U.S. (low sulfur diesel, catalytic converters, etc.), the net emission of PM₁₀ by diesel vehicles is relatively low. This is reflected by ambient PM₁₀ concentrations that are typically well below EPA critical thresholds. It is possible that the PM₁₀ burden imposed by trucks is not sufficient to cause mortality, but may show up through increased morbidity.
- 4) Location of population. The majority of PM₁₀ does not disperse very far from its origin. While several major highways travel through central Sacramento, most residential areas are somewhat removed from highways. This pattern is illustrated in Figure 5.

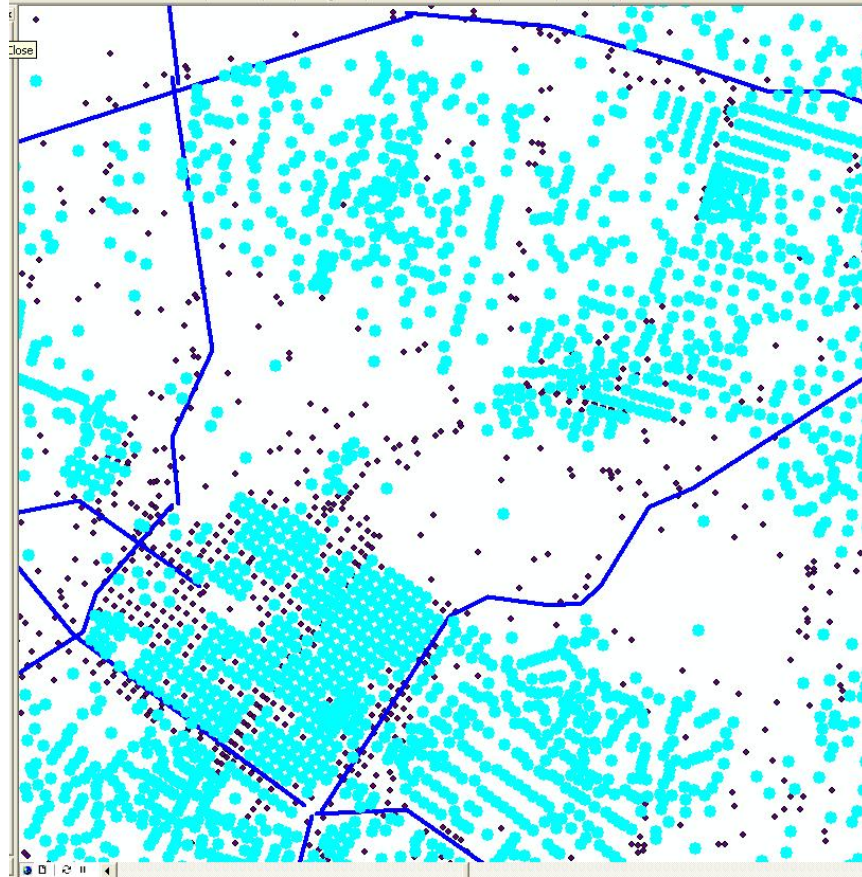


Figure 6 - A close view of central Sacramento. Census blocks with <5 population are shown in black, populated blocks in blue. Highways are dark blue lines. Note that many of the blocks adjacent to highways are low population.

This shows that many of the census blocks nearest the highway have little or no population.

These areas are largely commercial or light industrial and often form a buffer around the highways. This buffer will shield the heavy residential areas from feeling the effects of PM_{10} emitted on highways. In many areas, houses are shielded from the highway by walls or hedges, which would reduce the expected exposure to highway PM_{10} . Many zones near highways are for commercial or industrial use. The shielding effect may be somewhat overstated by the census data since people will often travel to these areas during the day to work. Without a more nuanced dispersion model or the ability to quantify emissions closer to residential areas, this effect may cause a significant underestimation of the health impacts of truck PM. An additional source of exposure not counted by this model is that of people while driving on

highways. The results of this dispersion clearly show that PM_{10} levels are elevated on highways, many people regularly spend time on these highways commuting to and from work.

- 5) Errors in dispersion. I was unable to locate a comprehensive set of weather data, which necessitated utilizing average prevailing winds. The effect of steady wind may be to speed dispersion of PM_{10} and transport away from populated areas. Sacramento is well known for long windless periods and thermal inversions, which may have the effect of trapping PM in populated areas longer than the dispersion model would indicate.
- 6) Only one pollutant species examined. It must be recognized that there may be significant health impacts from other pollutants. While PM is generally considered to have the greatest health impact of diesel emissions (assuming catalytic converters and standard emissions control technologies) the link between NO_x , CO and cardiovascular health has been made clear (Samet, Dominici et al., 2000). Existing literature generally accepts that these pollutants do not reach the same magnitude of harm as PM, but their effects are not evaluated or quantified by this study.
- 7) Lack of pollutant species interaction. When PM is emitted it often reacts with other pollutant species, changing both its aerodynamic and toxic properties. This effect has not been modeled in this thesis.

Discussion and Policy Implications of the Case Study

This case study demonstrates the method by which a policy analyst would use the analytic framework described in this thesis to test a hypothesis regarding the expected threat to public health from a subset of freight transport activity. Note that this methodology could be applied to other subsets, including other modes, other regions, or freight associated with one company or one or more development projects. In this case, the evidence indicates that diesel freight trucks, operating at steady speed on major highways, do not pose a significant public health risk in Sacramento, CA.

The case study has two results that bear upon this thesis. First, comparison with published literature does not indicate that there is a significant structural flaw in methodology. It appears that limitations in data and the underlying scenario assumptions did restrict the scope of this investigation; however the concept of GIS based dispersion modeling as a health impact estimation tool for local and regional policymakers appears to be intact. More extensive peer review would be required to conclusively validate the methodology, particularly whether sufficiently detailed data exist to facilitate micro-scale dispersion modeling and whether such detail improves the applicability and accuracy of results. Within the scope of available literature and expertise of the author, each subunit of the model appeared to produce a valid result and no unexpected incompatibilities between subunits arose. Further study is warranted to confirm both the explicit result of this project, that truck PM_{10} emissions on highways are a relatively small health risk, and the implicit result, that mortality from trucks arises from local activity, idling, congestion or other factors. While the overwhelming weight of literature suggests that trucks do present a public health risk, policy interventions to minimize these risks should focus primarily on reducing the presence of trucks in residential areas as well as improving traffic flow on highways to reduce the amount of intermittent driving trucks are subject to.

The second result of this case study is a structural validation of the techniques and methods employed in this analytical framework. Each modeling subunit (emission, dispersion and health impact) is demonstrated to work in a practical, generalizable way. While the location for the case study was chosen largely due to the availability of data, the necessary elements (vehicle counts, road maps, population maps, pollutant levels and weather) are all available for most, if not all, metropolitan areas in the U.S. and many international locations as well. There still exists a significant expertise requirement for locating and translating these data into a form usable by the model subunits, but this can be addressed in future work. Ultimately, this process allowed a non-expert in atmospheric dispersion to conduct a dispersion simulation and health impact analysis of the results, something that is generally not done by non-experts in the status quo. The steps required to integrate each subunit into the analytical process are relatively simple and could feasibly be automated by use of computer scripts or similar programmatic structures.

Future Policy Directions for Sacramento

Despite the great number of trucks traveling on Sacramento highways, the total quantity of emitted PM₁₀ remains relatively modest, especially when compared to fixed and non-anthropogenic sources (U.S. Environmental Protection Agency, 2008). PM₁₀ also tends to remain localized around the point of emission. Even though Sacramento highways pass through the center of the city, they are generally removed from residential areas by at least a few hundred meters, which gives the PM₁₀ emissions the opportunity to settle out of the air or otherwise dissipate (Zhu et al., 2002). While it is certainly possible that the low levels of health effects are an artifact of unsophisticated dispersion analysis (a fault entirely borne by the author), the results fall within the bounds expected of this analysis

and seem to reflect the general impression developed in literature: that it requires a significant shift in particulate concentrations to result in large-scale health impacts. Steady-state, highway emissions may be insufficient to produce such shifts.

This framework also gives direction to policy makers regarding efficient allocation of resources to emissions control programs. Certain technologies, such as hybrid fuel cells and anti-idling legislation can significantly reduce truck emissions during rest periods and during cargo transfer. The results of this case study indicate that such technologies may provide a public health benefit disproportionately greater than the amount of net emissions reduction resulting from such technology. This indicates that resources, both technological and political, may be best employed to increase utilization of these technologies and conversely, forcing adoption of technologies that reduce on-highway emissions may be a less efficient use of resources.

The case study also highlighted a significant missing element in the investigation of health impacts from freight transport. Accurate modeling of truck activity on arterial and local roads was difficult due to a lack of data. While the volume of activity on local roads is unlikely to exceed the volumes on highways, the closer proximity may outweigh the lower net emissions. To investigate this, an accurate assessment of local and arterial truck activity is needed, as well as more accurate emissions factors to reflect non-highway driving patterns². With these data, area or volume sources could be included to reflect local diesel truck activity.

² Ubanwa et al. estimate EF's using urban-simulation test patterns. These are established as uniform benchmarks and may not accurately reflect driving behavior.

This case study also informs a debate about freight policy in general. Due to environmental concerns, the movement of freight is being critically re-examined. Some freight flow policies consider utilizing a greater measure of truck transport, either to reduce time in transit or to reduce the need for intermodal transfers. While there may be significant GHG consequences associated with movement of freight by truck, as well as problems during intermittent driving cycles, this case study indicates there is limited public health penalty for using trucks for thru-hauls in urban areas. This result may allow policy makers greater flexibility in formulating freight transport policy over coming decades.

One area of particular interest is the expansion of intermodal freight, as well as increased freight traffic through West Coast ports. The port of Oakland, CA, is a major entry point for intermodal freight, though it processes significantly less volume than ports in Los Angeles, Long Beach and Tacoma. There may be potential to increase utilization of the port of Oakland as well as expand use of other San Francisco/San Pablo bay ports. One potential objection to such expansion is the health impacts of increased freight transit through Sacramento on its way to points east. This study indicates that such expansion may be feasible, from a public health standpoint, so long as the activity is confined to highways and traffic patterns do not become significantly more congested. This additional freight activity could also be routed east by train and the framework presented in this thesis could estimate the health impacts of such activity.

Implications of the Analytic Framework

Reduction of Expertise Requirements

The successful creation and use of the analytic framework described above demonstrates that health impact analyses, based on dispersion modeling, are possible. This is, of course, not a novel discovery since all of the principles have been well described in literature. The important realization is that many of the steps involved in performing such analyses could be automated. This serves two main functions: to reduce the time and cost of such analyses and to lower the threshold of expertise required. In the form presented in this thesis, the user must be familiar with dispersion modeling (to set up and operate the model), with file transfer operations (to accomplish the splitting and merging necessary to create the .asp file for ADMS, then to set up the health impact calculations) and large scale spreadsheet math (to apply the health impact calculations). Most, if not all, of these operations can be done without human interaction through computerization (see Future Work : Improvements). As it stands, the analytic framework promotes health impact analysis of freight transport by defining the procedure and collecting some of the necessary background data. A more automated model could reduce the burden on the user even farther.

Reducing the burden on users resolves a potential information asymmetry in many kinds of public policy decisions. In many cases, policy makers are obligated to make a trade-off between environmental protection and economic growth. Economic benefits have the advantage of being relatively immediate and concrete as compared to environmental benefits. A proposed project can be evaluated for economic benefits, such as job creation and tax revenue, with moderate accuracy. Predicting the environmental harms of a project can be significantly more difficult. Many projects would

lead to the emission of toxic air pollutants. Whether these pollutants would represent a significant public health hazard is open to debate. In the literature review and internet search, there appear to be no turnkey applications for analyzing the complete pollution cycle. This sort of analysis appears to be the province of specialists. The framework presented in this thesis demonstrates a method to reduce the complexity involved in conducting these analyses. This may allow more stakeholders the ability to perform health impact analyses and employ their results in the creation of policy. Expertise may still be required to guide the creation of analytic processes, evaluate uncertainty and interpret results. Future work will need to confirm that the simplifications imposed by the framework described in this thesis do not pose an unacceptable threat to the accuracy. Additional work may also be required to demonstrate whether this thesis actually facilitates health impact analyses by new groups of stakeholders.

Ultimately, this will help inform policy decisions as they relate to freight transport. The health impacts of development are not always given appropriate weight in making policy decisions, possibly because they are not adequately known. By having a more accessible tool for determining health impacts, policy makers can bring public health considerations into freight policy decisions.

The utility of a tool is ultimately determined by the hands of the wielder. It is certainly possible that the data requirements for even the most automated concept of this framework (accurate traffic data, pollutant background concentrations and maps) may be out of reach for some analysts. If the data availability and control issues can be resolved, the ability to conduct speculative analyses of freight policy should be greatly beneficial.

One area that must be examined in greater detail is the availability of meteorology data. This proved to be the most difficult to find, in an appropriate format for use with ADMS. This may be due to

the author's lack of expertise in meteorology or a limitation of ADMS. ADMS is primarily applied in Europe and its meteorology data input formats appear to be optimized to allow easy utilization of automated weather data collected in European standard formats. Utilization of average prevailing winds, as was done in this project, limits the accuracy of dispersion modeling.

Local and Regional Issues

Economic policy debates often come down to the issue of location. Almost everyone is in favor of economic growth. Almost everyone is against economic growth in their particular neighborhood. The Not-In-My-Back-Yard (NIMBY) problem is one that no local or regional policy maker can afford to ignore. Policy should respect the wishes of communities, but often no community is willing to accept the presence of industrial or large-scale transport activity.

In many cases, the information asymmetry discussed above contributes to this phenomenon too. Without a reliable, low-cost method of evaluating the public health impacts of economic development, decisions may be made on incomplete information. In some cases, the perception of health harm may exceed the reality. In early, informal investigations using this model, several instances of hypothetical industrial development near residential areas were considered. In general, the presence of a moderate number of trucks, even in residential areas, does not pose a significant health risk to the population. This is not to say that such activity is entirely benign, but rather that there is often a perception of harm where no evidence of actual harm exists.

Similarly, development often occurs without adequate information regarding health hazards being disseminated to the community. Environmental impact reporting is a necessary part of

development planning, but often occurs after the process has gained momentum. Additionally, most environmental impact reports are funded by developers and produced in dense language inaccessible to non-experts. In both cases, there is a fundamental lack of accurate information in the local and regional development process. Micro-scale dispersion modeling³ may not be a reasonable goal of an analytic framework that seeks to be accessible to non-experts, but the processes described could serve as a threshold test for health impacts. The model could be used to determine where the potential for significant public health problems exists and allow more detailed examinations to be conducted.

Developing World Issues

The United States has enacted several diesel emissions control measures over the last five years, including Ultra-Low Sulfur Diesel Fuel (ULSD), catalytic converters and other exhaust emissions control technology. U.S. roads are also typically paved and generally well maintained, which reduces re-suspension of particulate matter (Furusjo et al., 2007). Many developing economies have more severe PM pollution problems, to which transportation is a major contributor (Badami, 2005; Chandrasiri, 2006). Despite the health impacts of transport growth, many developing economies project significant growth in the amount of transport activity over the coming decades (Asian Development Bank, 2006).

In developing economies, the investment necessary to lower emissions through more advanced technology may be beyond the reach of many actors. Emissions control technology may need to be reserved for vehicles on routes that pose a high risk to public health. The availability of a simple, low cost health impact model in the developing economies may promote more efficient selection of routes,

³ Resolution in the tens to hundreds of meters, necessary for quantifying impacts from small projects.

improved freight transport policy and optimal assignment of limited technological capital to reduce emissions.

The unique difference between application in the U.S. or other developed economies, as I have presented in this thesis, and application in developing economies is that the most developed economies have already picked the “low-hanging fruit” of emissions control and reaped the greater portion of available health benefit from doing so. Many developing economies, notably China and India, have significant public health problems stemming from air pollution and fossil fuel combustion. The potential health benefits available to these countries from improved freight transport policy are likely to greatly outweigh the likely benefits in the U.S. or Europe.

Future Work

Corrections

The model presented in this thesis is, admittedly, a very rough sketch of what a final product would look like. The model, as presented, contains a great number of assumptions and shortcuts that would need to be addressed in order to create a robust and accurate final product.

1. A valid model would seek to account for the presence of freight activity on arterial roads. As demonstrated by the Sacramento case study, the activity of trucks on major highways is a relatively small fraction of total health impacts from particulate matter. A more accurate model would take activity on smaller roads into account, either by adding additional line sources for smaller roads, or by approximating truck activity on smaller roads as an area source. The

accuracy of either of these options would be dependent on the availability of data regarding truck flows outside of major highways (or assumptions regarding such activity).

2. The interface for describing routes needs to be significantly improved. The hand tracing is cumbersome and inaccurate; it is only used because it is the available method of graphical input available through ADMS. Ideally, the emissions quantification module would be able to directly import road geometry from the appropriate map files and directly compute emissions thereon.
3. ADMS does not appear to be well-suited for a deployment version of this model. While it has the advantages of simplicity and robust simulation, it is limited by its lack of scripting interface and its maximum 10,000 output points. Additionally, it is a copyrighted product of a private consultancy. License to use the software was granted for the purposes of this thesis, but we should assume that future applications must be paid for. There are several atmospheric dispersion models, including CALINE and AEROMOD, which are publicly available and at least as accurate as ADMS, though they require more expertise to use.
4. The assumptions regarding atmospheric conditions and dispersion need to be examined and, likely, modified. The capability of dispersion models to yield accurate simulations is largely dependent on the provisions of accurate atmospheric conditions. I lack the expertise to provide anything more than rough estimates of atmospheric conditions (there are data available, but many of them require significant interpretation to be formatted for utilization by ADMS). There will, doubtless, need to be some simplifying assumptions made in order to make this model usable by operators with modest levels of expertise in the field; I am not qualified to define or discuss those assumptions at this juncture.
5. One of the defining problems of environmental analysis is access to data. Governments, as well as non-governmental actors, are improving the quality and scope of data available. These data are often hard to find, however, and are often presented in inconvenient formats. It may not be

reasonable to expect that an analyst would have immediate access to all necessary data to run an accurate scenario. A final version of this model should include at least a list of available data sources for as many areas as possible. Ideally, the model should be able to access online databases and retrieve the information itself. This is particularly important for weather data, which are typically stored in formats described largely by terms of meteorology art, which are inaccessible to non-experts. Weather information is regularly recorded by many governmental agencies (U.S. and foreign) and often made available in online databases. An ideal model would automate collection of this data, using the extents of the selected routes or population areas to locate the appropriate data. This process may get complicated as the model attempts to expand its scope to less-developed nations, in which case simplifying assumptions may be necessary.

6. Atmospheric dispersion modeling is exceedingly complicated. I realize that my level of expertise is not enough to do this problem justice. A more detailed and elegant approach to dispersion modeling may significantly change our results. This thesis demonstrates that the three subunits, which have often been used as singular “black-box” type operators for other uses can be linked together in sequence. The boxes used in this particular thesis may be replaced with more sophisticated versions in the future, but the same analytic framework will hold.
7. Health impact calculations may want to include more morbidities than just cardiopulmonary disease and lung cancer.
8. Additional pollutant species are likely to be very significant, though more complicated to evaluate. PM_{10} is only one of many health-hazardous pollutants. $PM_{2.5}$ should be included as a separate species, due to its different dispersion characteristics. NO_x and VOC's are also significantly toxic and should be considered.
9. An extremely difficult, though optional improvement would be to automate the population of freight activity onto routes. Most freight activity is counted using notation and terminology that

appears to vary from state to state. Often, the official name of a route does not match the name commonly listed on maps. In many cases, the data is stored in a PDF file, which is difficult to read by machine. I found during this process that it took a significant amount of time to interpret the traffic flow data from the California Department of Transportation and correctly translate it onto the shapefiles and routes used by ADMS. If I were not familiar with the highway networks in the Sacramento region, this task would have been even more difficult. It may be impractical to attempt to create a computer script or program that can interpret all potential versions of traffic data across states and convert it to appropriate input formats for dispersion models.

10. Several other techniques exist for health impact calculation (Akeson et al., 2000). These should be included for comparison to the method of Ostro (2004). Additionally, β values and incidence rates are derived from empirical epidemiology. A more thorough examination of the subject may help.

Improvements



The ultimate goal of this project is to be a step towards the creation of a system that would reduce the expertise requirements to conduct this sort of health impact analysis. This goal was reached insofar as a demonstration of the process allows. The techniques described above are only a partial fulfillment of this goal, since they require several steps to format data and transfer it between model subunits. Additionally, the implementation of Ostro's health impact calculations requires case-by-case calculations using Excel. Setup of the dispersion model is still accomplished manually. While it is entirely impossible to remove most or all human expertise from the equation, the time and knowledge requirements of this analysis can be significantly reduced using programming structures. At most steps



of this analysis I attempted to define (or at least assert) the methods by which steps could be incorporated into a computational infrastructure. Appendix A documents the steps necessary to use the models, and provides notes on automating these steps.

The details of this infrastructure must, necessarily, be left to experts in the field to be done successfully. In general, two potential structures exist for automation: scripting and High-Level Architecture (HLA) (IEEE, 2000; Lightner & Dahmann, 1999).

Scripting involves creation of several procedural programs or “scripts” that will interface with ArcGIS, ADMS (or other dispersion model) and the program used to perform the health-impact calculations (Excel in this thesis, though any mathematical operations package could accomplish the same thing). The scripts instruct the programs on the operations to carry out as well as the steps required to transfer data to other subunits (Figure 6).

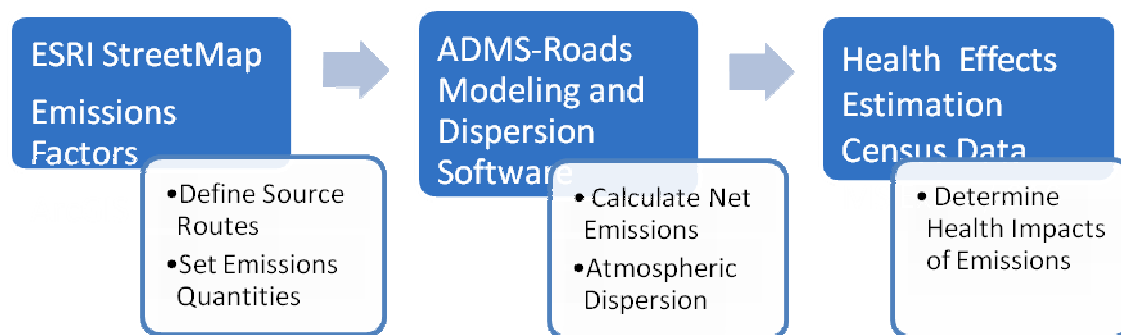


Figure 7 - An operational diagram of the analytic framework. The arrows represent scripts used to direct the flow of data. See Appendix A for details regarding integration of units and data flow.

Scripting is relatively simple to implement and has demonstrated compatibility with ArcGIS as well as several mathematics packages. The disadvantage is that it is relatively intolerant of errors and often requires significant case-by-case modification to adapt to non-standard analytical processes.

The other alternative is to use a more formal programmatic method, such as HLA (Figure 7). Under HLA, a central process known as a run-time infrastructure (RTI), serves as a communications hub for all modeling subunits. Rather than being triggered by scripted procedures, each programming subunit operates independently. The RTI keeps track of state changes in each subunit. When one subunit completes a process and produces an output, the RTI alerts all other subunits of the availability of the output and facilitates transfer to any programs that require it. This is known as a “Publish-and-subscribe” architecture; outputs from program subunits are “published” or made available through the RTI to other subunits who “subscribe” to the outputs of the publishing subunit. This architecture was described by Dahmann, Fujimoto and Weatherly in 1998 (Lightner & Dahmann, 1999) and has been stabilized by promulgation of IEEE standards (IEEE, 2000) .

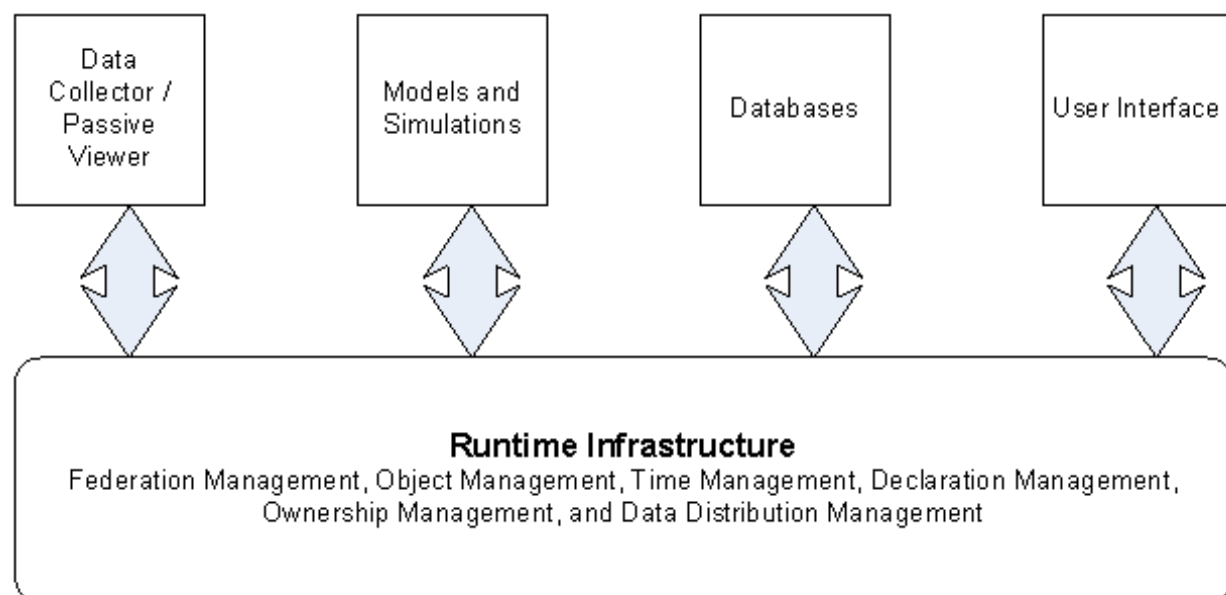


Figure 8 - A schematic of HLA. Subunits interface with the Runtime Infrastructure through the Publish and Subscribe process. Graphic courtesy of Sidney Pendelberry

The advantage of HLA is that it is robust and tolerant of errors, since the operational process is not necessarily a linear sequence which could be interrupted at any time. Its disadvantages are that it is complex and resource intensive to set up and requires significant computational resources. For a model that includes only three subunits it may be overkill, though it would potentially be the most flexible for future modification or addition.

The sequence of processes described by this thesis lend themselves to programmatic automation. Doing so will simplify the experience for the user and reduce the expertise requirements for conducting health impact analyses.

Future Directions

This thesis and case study highlight some of the gaps in literature as they pertain to determining the health impacts of freight activity. While the following issues are beyond the scope of this project, and future iterations thereof, they would contribute to the field.

- 1) The case study demonstrated that it is likely that on-highway emissions play a relatively small role in the public health impacts of air pollution. Whether freight transport in general is a significant public health problem remains unanswered. Several studies have demonstrated that areas of unusually high levels of freight activity, such as major ports or high-traffic routes, suffer health harms (Starcrest Consulting, 2006; Xiao et al., 2006). An important question is whether cities with moderate freight transportation activity also suffer harms. This effort could be assisted in two ways.

- a. Epidemiological studies of health in areas with high activity as compared to those in low.

This cannot directly establish causality, but can make a correlative link and allow validation of causal models.
 - b. Measurement of off-highway freight activity. Most dispersion models can model area sources of emissions. Creation of an accepted value of the typical emissions per square mile of various zoning types (commercial, light industrial, etc.) would allow more accurate attribution of non-highway freight activity. Alternatively, values for truck activity on major and minor surface streets could suffice as well.
- 2) Better attribution of the source of background PM emissions. Anthropogenic PM is a small fraction of the total in many areas, falling well short of fires, agricultural activity and unpaved road dust. Urban areas tend to be dominated by combustion and vehicle emissions. Clearer delineation of typical urban background levels as well as the source of these pollutants would be helpful as would be a clear sense of what portion of background PM is anthropogenic as well as what part is due to diesel engine exhaust. There have been a few studies that do precisely this, but only a tiny fraction of urban areas have had their PM₁₀ emissions so catalogued.
 - 3) Better integration of pollution data with meteorological data. Pollutant levels are highly dependent on wind and precipitation levels. While historical data for both types exist, it is often difficult to easily model the interaction between the two. Given the close association of the two it would benefit researchers to see a common format as well as a single source of data.

Conclusion

This thesis describes and demonstrates the analytic framework by which predictive health impact modeling of diesel freight may be accomplished. This is done by breaking the analytic process into three subunits, emission, dispersion and health impact quantification. Each subunit is joined together by transfer of data; the output of the preceding unit is used as the input to the subsequent unit. Additionally, the processes necessary to find input data and accomplish the transfer between subunits was described. These processes are of the type that can be accomplished programmatically, which provides a blueprint for future work.



The analytic process was employed on a test case, which examined the health impacts of diesel freight trucks on highways in Sacramento, California. While there were some difficulties in converting weather data to an appropriate format for the dispersion model, these difficulties are primarily caused by the author's lack of expertise in the field of meteorology and dispersion modeling.



The problems encountered by this thesis do not, in the opinion of the author, indicate that the underlying analytic framework is flawed. Each modeling subunit can be viewed as a black box, requiring data input and producing data output. The specific implementations of the black boxes chosen for this thesis were picked largely due to expertise and time constraints. More accurate black box implementations could be substituted in future models, utilizing the same type of inputs and outputs, to produce a more accurate result. The purpose of this thesis, to take the first step towards describing a generalizable analytic tool to simplify health impact prediction, was accomplished.

In doing so, several important policy issues were uncovered. First, there is evidence to believe that the majority of health impacts from diesel freight emissions are not due to on-highway trucks traveling at steady speeds. This implies that improvements to public health by reducing freight

transport emissions need to focus on other areas, such as surface street traffic, idling, stop-and-go driving and freight transfer points.

Additionally, there is evidence to believe that the public health impact of diesel freight trucks, in most parts of the U.S., is relatively limited. The rough estimations derived from the California Goods Movement study, indicate that the maximum health impact in Sacramento from freight is relatively small, on the order of tens of deaths per year for the population in this study. With improvements to diesel emissions regulation already made in the status quo, there might be more efficient ways to achieve better public health in the U.S. than by reducing emissions from freight transport. Developing nations, on the other hand, are experiencing significant health harms from air pollution already and project major growth in diesel freight vehicles over the coming decades. The need for considered transport planning may be greater outside of the U.S. and a tool such as the one described by this thesis could be of help.

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Appendix A: Operating Instructions

These instructions are provided as a general overview of the program processes utilized in this thesis as well as some ideas regarding ways in which the analysis could be made simpler for the user. These directions are specific to the software packages used for this thesis (ArcGIS 9.x, ADMS, Microsoft Excel) and would require modification if other programs were substituted.

Operator Instructions for Model as Developed	Comments Regarding Programmatic Automation
<ol style="list-style-type: none">1. Open an instance of ArcMap and ADMS.2. Load a map describing road geometry in the area to be study. For U.S. regions, this data is easily available from ESRI's Streetmap 2007 dataset. Note that this map must be converted to a projection that uses meters as its unit of measurement, such as North American Equidistant Conic Projection.3. Load the population data file that will be used to assign health impacts. Ensure that its units of measurement are also in meters. Population data is included in ESRI's Streetmap 2007 package. Using population data recorded as centroids of census blocks is recommended.4. Select the "Add Road Source" tool from the ADMS toolbar and use the tool to trace over the roads which will be routes to analyze.	<ol style="list-style-type: none">1. These steps could be automated, though they are simple enough to leave as a manual action.2. The selection of roads requires user interaction, but a more accurate description of roads could be obtained by using the Trace tool, which creates line

<ol style="list-style-type: none"> 5. Repeat step 3 as necessary to add each route. 6. Select the points on the population map that will be analyzed. When using population data that represents centroids of census blocks, simply select an area that encompasses all routes under study, with a significant buffer in all directions. Export these points to a comma separated text file for later use. 7. Input emissions factors (EFs) for each route. In ADMS, this can be accomplished using built in per-vehicle EFs and inputting the number of vehicles per hour. Alternatively, EFs can be calculated according to equation (1) above. In the case studies, the value of .237 g PM10 per truck*mile was used, as noted in the methodology section. This converted to a linear emission factor of 4.1×10^{-5} g PM10 per truck*km*second. 8. Enter meteorology data for study area. Ideally, one would have yearlong meteorology data, in order to account for seasonality. In absence of detailed data, average prevailing winds, temperature, boundary layer thickness etc. can be imported or ADMS default values used. ADMS also requests Monin-Obukhov length. This figure is just estimated using representative values suggested by ADMS. In the case study, metropolitan area data from www.weatherexplained.com was used. 	<p>segments that follow the contours of existing edges. These edges could then be directly imported into ADMS (or other dispersion models) as the routes of emitting freight activity.</p> <ol style="list-style-type: none"> 3. The calculation of linear emission factors can be done by script external to the dispersion model, or be done as field calculations ArcGIS and imported into the dispersion model along with the routes. 4. Ideally, an automated system would be able to connect to online atmospheric databases and retrieve representative climatic data. Such automated retrievals are within reasonable programming limits and would operate as follows: <ol style="list-style-type: none"> a. Set evaluation area, defined by the extent of routes under evaluation. b. Check area against climatic databases to see if any monitoring stations exist inside evaluation area. If multiple stations exist, pick which to use (either user-defined or by station
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<p>9. Enter background pollutant concentration. This data can be found from the EPA AirData website www.epa.gov/air/data/geosel.html.</p> <p>10. Assign output grids and/or points. If using population data in the form of points, then input those points as locations at which to calculate pollutant concentration. From the comma separated text file exported in step 6, select the variables containing name (ID), X coordinate, Y coordinate and Z coordinate of each point (Z value may need to be manually set to zero, when dealing with a projected map as in the case study) and saving the resulting file as a .asp file, in the same directory as the ADMS working files, with the same file name as the project files.</p> <p>11. Select species of pollutant being examined.</p> <p>12. Run model in ADMS.</p> <p>13. ADMS will generate a comma-separated text file with a .plt extension. Merge the population data file into this file by name (ID) value. This will associate the population of each point with the pollutant concentration projected by the dispersion model.</p> <p>14. In Excel, or other mathematics program,</p>	<p>closest to centroid of evaluation area).</p> <p>c. If no station inside evaluation area, select closest station. If no station is within a critical distance, report lack of data to user and prompt for manual input.</p> <p>5. This step could also be automated in similar fashion to the meteorological data step above.</p> <p>The user will have to define grid output or point output. Based on that, the program will either set the appropriate grid size or select the points. If using population data based on polygons, then output should be in the form of grids of a resolution determined by programmatic or computational limitations. ADMS can handle up to 10,000 grid points and runs quickly on a Pentium IV processor. Population exposure can then be calculated by geometric overlay of grid cells on population polygons or by kriging. Utilization of polygon-based population data is more computationally complex but has been validated in literature (Georgopoulos et al., 2005)</p> <p>6. The manipulation of variables inside a comma separated text file is comparatively simple and easy to accomplish by script.</p> <p>7. To reduce computational burden, census blocks with zero population may be</p>
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<p>apply the health impact equations of Ostro, as described in equations (2)-(5)⁴.</p> <ul style="list-style-type: none"> a. Mortality can be calculated for cardiopulmonary disease and lung/bronchial cancer. Use β from Table 1. Using the high and low values for β provides a basic analysis of sensitivity to changing health impact assumptions. b. Calculation will be conducted for each census block and the total values summed across all blocks. c. If the graphical display capability is available, displaying the resultant map of pollutant concentration or health impacts can aid in analysis. 	<p>omitted, though this will render graphical display of the output inaccurate.</p>
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⁴ The equations determine health impact from the difference between baseline levels and post-study levels. The baseline levels taken from monitoring stations may, depending on the scenario being considered, already take into account the effects of the specified freight transport activities. The baseline levels may need to be adjusted to reflect this. See discussion in the Case Study section for details.